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1. REPORT DATE 19 FEB 2010	2. REPORT TYPE	3. DATES COVERED 00-00-2010 to 00-00-2010		
4. TITLE AND SUBTITLE Kepler Planet-Detection Mission: Introduction And First Results			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) United States Naval Observatory,Flagstaff,AZ,86001			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES SCIENCE, VOL 327, 19 FEBRUARY 2010				
14. ABSTRACT <p>The Kepler mission was designed to determine the frequency of Earth-sized planets in and near the habitable zone of Sun-like stars. The habitable zone is the region where planetary temperatures are suitable for water to exist on a planet's surface. During the first 6 weeks of observations, Kepler monitored 156,000 stars, and five new exoplanets with sizes between 0.37 and 1.6 Jupiter radii and orbital periods from 3.2 to 4.9 days were discovered. The density of the Neptune-sized Kepler-4b is similar to that of Neptune and GJ 436b, even though the irradiation level is 800,000 times higher. Kepler-7b is one of the lowest-density planets (~0.17 gram per cubic centimeter) yet detected. Kepler-5b, -6b, and -8b confirm the existence of planets with densities lower than those predicted for gas giant planets.</p>				
15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 5
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified		

Kepler Planet-Detection Mission: Introduction and First Results

William J. Borucki,^{1*} David Koch,¹ Gibor Basri,² Natalie Batalha,³ Timothy Brown,⁴ Douglas Caldwell,⁵ John Caldwell,¹⁷ Jørgen Christensen-Dalsgaard,⁶ William D. Cochran,⁷ Edna DeVore,⁵ Edward W. Dunham,⁸ Andrea K. Dupree,¹⁰ Thomas N. Gautier III,⁹ John C. Geary,¹⁰ Ronald Gilliland,¹¹ Alan Gould,¹⁸ Steve B. Howell,¹⁵ Jon M. Jenkins,⁵ Yoji Kondo,²⁹ David W. Latham,¹⁰ Geoffrey W. Marcy,² Søren Meibom,¹⁰ Hans Kjeldsen,⁶ Jack J. Lissauer,¹ David G. Monet,¹² David Morrison,¹ Dimitar Sasselov,¹⁰ Jill Tarter,⁵ Alan Boss,¹⁹ Don Brownlee,²¹ Toby Owen,²⁰ Derek Buzasi,²² David Charbonneau,¹⁰ Laurence Doyle,⁵ Jonathan Fortney,²⁴ Eric B. Ford,¹³ Matthew J. Holman,¹⁰ Sara Seager,²⁵ Jason H. Steffen,²⁶ William F. Welsh,²⁷ Jason Rowe,¹ Howard Anderson,² Lars Buchhave,¹⁰ David Ciardi,²⁸ Lucianne Walkowicz,² William Sherry,¹⁵ Elliott Horch,²³ Howard Isaacson,² Mark E. Everett,¹⁴ Debra Fischer,¹⁶ Guillermo Torres,¹⁰ John Asher Johnson,²⁸ Michael Endl,⁷ Phillip MacQueen,⁷ Stephen T. Bryson,¹ Jessie Dotson,¹ Michael Haas,¹ Jeffrey Kolodziejczak,³⁰ Jeffrey Van Cleve,⁵ Hema Chandrasekaran,⁵ Joseph D. Twicken,⁵ Elisa V. Quintana,⁵ Bruce D. Clarke,⁵ Christopher Allen,³¹ Jie Li,⁵ Haley Wu,⁵ Peter Tenenbaum,⁵ Ekaterina Verner,³² Frederick Bruhweiler,³² Jason Barnes,³³ Andrej Prsa³⁴

The Kepler mission was designed to determine the frequency of Earth-sized planets in and near the habitable zone of Sun-like stars. The habitable zone is the region where planetary temperatures are suitable for water to exist on a planet's surface. During the first 6 weeks of observations, Kepler monitored 156,000 stars, and five new exoplanets with sizes between 0.37 and 1.6 Jupiter radii and orbital periods from 3.2 to 4.9 days were discovered. The density of the Neptune-sized Kepler-4b is similar to that of Neptune and GJ 436b, even though the irradiation level is 800,000 times higher. Kepler-7b is one of the lowest-density planets (\sim 0.17 gram per cubic centimeter) yet detected. Kepler-5b, -6b, and -8b confirm the existence of planets with densities lower than those predicted for gas giant planets.

Since the first discoveries of planetary companions around pulsars (1, 2) and normal stars (3), more than 400 such

planets have been detected. Most of these are giant planets, often more massive than Jupiter. Many have a semimajor axis (mean star/planet

separation) of less than 1 astronomical unit (AU, the distance between Earth and the Sun) and/or high eccentricity. These surprisingly small semimajor axes suggest that many planets form at

¹NASA Ames Research Center, Moffett Field, CA 94035, USA.

²University of California, Berkeley, CA 94720, USA. ³San Jose

State University, San Jose, CA 95192, USA. ⁴Las Cumbres

Observatory Global Telescope, Goleta, CA 93117, USA. ⁵SETI

Institute, Mountain View, CA 94043, USA. ⁶Aarhus University,

Aarhus, Denmark. ⁷McDonald Observatory, University of Texas

at Austin, Austin, TX 78712, USA. ⁸Lowell Observatory, Flagstaff,

AZ 86001, USA. ⁹Jet Propulsion Laboratory, California Institute

of Technology, Pasadena, CA 91109, USA. ¹⁰Harvard-

Smithsonian Center for Astrophysics, Cambridge, MA 02138,

USA. ¹¹Space Telescope Science Institute, Baltimore, MD

21218, USA. ¹²United States Naval Observatory, Flagstaff, AZ

86001, USA. ¹³University of Florida, Gainesville, FL 32611,

USA. ¹⁴Planetary Science Institute, Tucson, AZ 85719, USA.

¹⁵National Optical Astronomy Observatory, Tucson, AZ 85719,

USA. ¹⁶Yale University, New Haven, CT 06520, USA. ¹⁷Yale

University, North York, M3J 1P3 Ontario, Canada. ¹⁸Lawrence

Hall of Science, Berkeley, CA 94720, USA. ¹⁹Carnegie

Institute of Washington, Washington, DC 20015 USA. ²⁰University

of Hawaii, Hilo, HI 96720 USA. ²¹University of Washington,

Seattle, WA 98195, USA. ²²Eureka Scientific, Oakland, CA

94602, USA. ²³Southern Connecticut State University, New

Haven, CT 06515, USA. ²⁴University of California, Santa Cruz,

CA 95064, USA. ²⁵Massachusetts Institute of Technology,

Cambridge, MA 02139, USA. ²⁶Fermilab, Batavia, IL 60510,

USA. ²⁷San Diego State University, San Diego, CA 92182, USA.

²⁸Exoplanet Science Institute/Caltech, Pasadena, CA 91125,

USA. ²⁹NASA Goddard Space Flight Center, Greenbelt, MD

20205, USA. ³⁰Marshall Space Flight Center, Huntsville, AL

35805, USA. ³¹Orbital Sciences, Mountain View, CA 94043,

USA. ³²Catholic University of America, Washington, DC 20064,

USA. ³³University of Idaho, Moscow, ID 83844, USA.

³⁴Villanova University, Villanova, PA 19085, USA.

*To whom correspondence should be addressed. E-mail: William.J.Borucki@nasa.gov

several astronomical units from their stars before migrating to their current locations. The processes that terminate the inward migration and the fraction of planets that fall into their stars are not known. Although the inward migration of a giant planet is expected to remove inner, smaller planets by scattering them into the star or out of the planetary system, a second generation of planets might reaccrete in the wake of the migrating planet (4). Because it is difficult to predict or detect terrestrial planets, their frequency and distributions are unknown.

Kepler includes a differential photometer with a wide (115 square degrees) field of view (FOV) that continuously and simultaneously monitors the brightness of approximately 150,000 main-sequence stars. The photometer is based on a modified Schmidt telescope design that uses a corrector with a 0.95-m aperture and a 1.4-m diameter $f/1$ primary mirror. The aperture is sufficient to reduce the Poisson noise to the level that is required to obtain a 4σ detection for a single transit from an Earth-sized planet passing in front of a 12th-magnitude G2 dwarf (that is, a Sun-like star) with a 6.5-hour transit. The mission was launched on 6 March 2009 into an Earth-trailing orbit. Its design, characteristics, selection of target stars, on-orbit performance, data processing pipeline, data characteristics, and mis-

sion operations can be found in the supporting online material (SOM) text, section 1, and (5–11).

Here we describe the detection of five new exoplanets of varying size and orbital period based on the first two data segments taken at the start of the mission, and we provide some comparisons with previous detections. The first segment is a 9.7-day period (Q0) starting on 2 May 2009 universal time (UT) during the commissioning phase. The second is a 33.5-day period (Q1) taken at the beginning of science operations on 13 May 2009 UT. For Q0, oversized apertures were used to image each star, because the point-spread function and geometry of the focal plane were not yet known precisely. During this period, nearly all stars brighter than $V = 13.6$ magnitude in the FOV were observed (52,496 in total). Analysis of these data sets also led to a series of astrophysical discoveries, including oscillations of giant stars and two examples of planet-sized objects that are hotter than the stars they orbit (12–21).

The Q1 observations used smaller apertures, which allowed 156,097 objects to be observed. Targets were chosen to maximize the number of stars that were both bright and small enough to show detectable transit signals for small planets in and near the habitable zone (HZ) [SOM text 2 (11)].

Planets orbiting close to hot stars can reach temperatures in excess of 2000 K and can emit enough light for Kepler to detect their thermal radiation in the range of visible wavelengths. Kepler's first observations detected thermal emission from exoplanet HAT-P-7b (22, 23). The phase curve of the emission provided information about the planetary albedo, the depth of absorption in the planet's atmosphere, and the lack of redistribution of the energy to the night side of the planet. Analysis of the first data set led to the discovery of ellipsoidal variations in the host star (24).

Several planetary candidates that passed the tests to remove false-positive events (SOM text 3) were observed with radial velocity (RV) spectrometers to determine their masses. (See SOM text 4 for the approach used to determine the characteristics of the planets from the observations.) Modeling was performed to establish the system characteristics and uncertainties (25). Each target has a Kepler identification number (KIC no.) from the Kepler Input Catalog (KIC), but each confirmed exoplanet is also assigned a convenient abbreviation (Kepler-number-letter) (Tables 1 and 2). The numbering begins with 4b, because the designations 1b, 2b, and 3b are used to refer to previously known exoplanets in the Kepler FOV: TrES-2 (26), HAT-P-7b (22), and HAT-P-11b (27), respectively.

Table 1. Properties of the exoplanets detected by Kepler. The state of the current observations is insufficient to support claims of nonzero eccentricity. Therefore, parameter estimates are based on the assumption of a circular orbit. Calculations of the equilibrium temperatures

assume a Bond albedo = 0.1 and efficient transport of heat to the night side. Epoch = HJD-2454900.0. R_J is the Jupiter equatorial radius. M_J is the mass of Jupiter. Errors are $\pm 1\sigma$ and represent formal errors only.

Identification	KIC no.	Period (days)	Epoch	Radius (R_J)	Mass (M_J)	Density (g/cm ³)	Equilibrium temperature (K)	Semimajor axis (AU)	Inclination (degrees)	Reference
Kepler-4b	11853905	3.21346 ± 0.00022	56.6127 ± 0.0015	0.357 ± 0.021	0.077 ± 0.012	1.91 ± 0.41	1650 ± 200	0.04558 ± 0.00087	89.76 ± 1.17	(25)
Kepler-5b	8191672	3.548460 ± 0.000032	55.90122 ± 0.00021	1.431 ± 0.048	2.114 ± 0.064	0.894 ± 0.079	1868 ± 284	0.05064 ± 0.00070	86.3 ± 0.6	(30)
Kepler-6b	10874614	3.234723 ± 0.000017	54.48636 ± 0.00014	1.323 ± 0.026	0.669 ± 0.027	0.352 ± 0.019	1500 ± 200	0.04567 ± 0.00050	86.8 ± 0.3	(29)
Kepler-7b	5780885	4.885525 ± 0.000039	67.27567 ± 0.00014	1.478 ± 0.051	0.433 ± 0.040	0.166 ± 0.019	1540 ± 200	0.06224 ± 0.00127	86.5 ± 0.4	(28)
Kepler-8b	6922244	3.52254 ± 0.00004	54.1182 ± 0.0003	1.419 ± 0.055	0.603 ± 0.154	0.261 ± 0.071	1764 ± 200	0.0483 ± 0.0008	84.07 ± 0.33	(31)

Table 2. Characteristics of the stars hosting Kepler planets. K_p is the stellar magnitude calculated for the Kepler band pass. The values are similar to those produced by an R filter (7) for most star types. Right ascension (RA) and declination (dec) refer to the J2000.0 equinox. For three of the stars (Kepler-4, -5, and -7), the model fits give two peaks in the distributions of

the mass and radius. The values listed here are thought to be the best estimate (25, 28–31). $\log(g)$ values are calculated from model fit based on stellar density and temperature. T_{eff} , effective temperature. M^* and R^* are the mass and radius of the host stars, respectively. M_{Sun} and R_{Sun} are the mass and radius of the Sun, respectively.

Identification	M^* (M_{Sun})	R^* (R_{Sun})	$\log(g)$ (cgs)	[Fe/H]	T_{eff} (K)	K_p (mag)	RA, dec (hour, degree)
Kepler-4	1.223 ± 0.068	1.487 ± 0.084	4.165 ± 0.037	$+0.17 \pm 0.06$	5857 ± 60	12.21	19.04102, 50.13575
Kepler-5	1.374 ± 0.056	1.793 ± 0.053	4.067 ± 0.020	$+0.04 \pm 0.06$	6297 ± 60	13.4	19.96047, 44.03505
Kepler-6	1.209 ± 0.040	1.391 ± 0.024	4.236 ± 0.011	$+0.34 \pm 0.06$	5647 ± 44	13.3	19.78915, 48.23994
Kepler-7	1.347 ± 0.080	1.843 ± 0.057	4.030 ± 0.018	$+0.11 \pm 0.03$	5933 ± 44	12.9	19.23877, 41.08981
Kepler-8	1.213 ± 0.063	1.486 ± 0.056	4.174 ± 0.026	-0.055 ± 0.033	6213 ± 75	13.6	18.75254, 42.45108

Fig. 1. Comparison of mass versus semimajor axes for Kepler planets. Circles represent transiting planets listed in the Extrasolar Planets Encyclopedia (37).

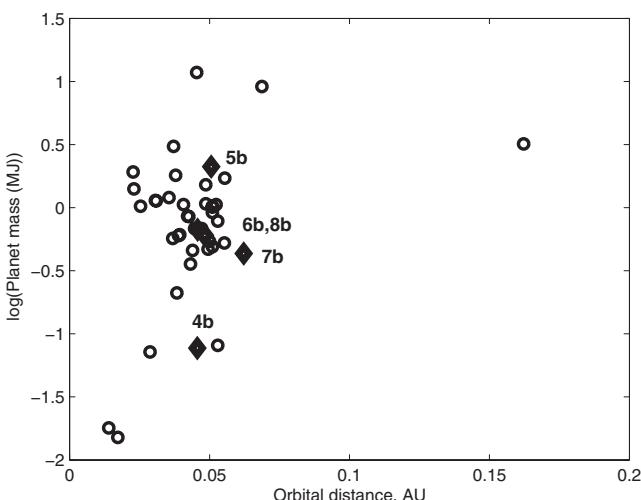


Fig. 2. Comparison of stars associated with the Kepler exoplanets with those associated with the planets in the Extrasolar Planet Encyclopedia. The parameter plotted on the vertical axis is the ratio of the area of the star multiplied by its effective temperature to the fourth power divided by solar values.

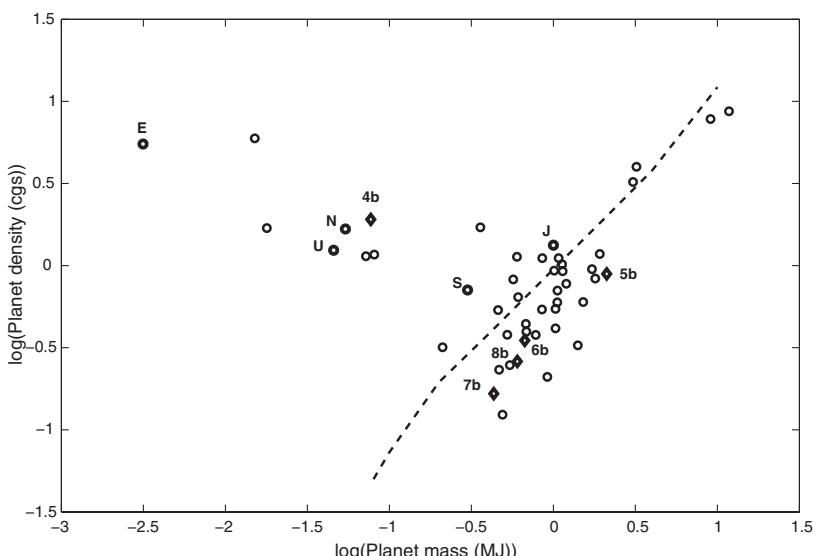
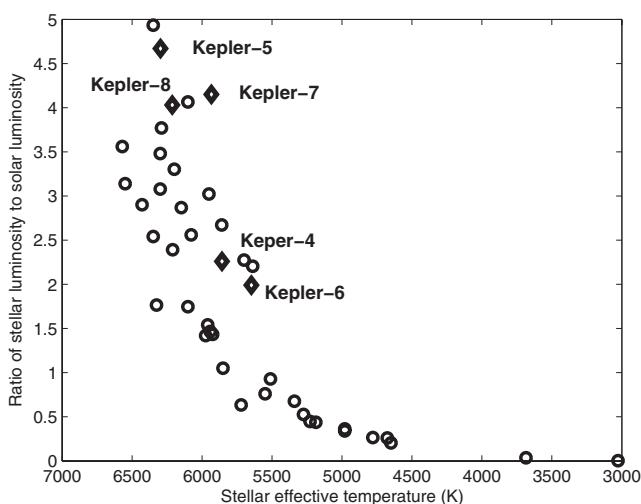


Fig. 3. Planet density versus mass. Kepler planets are shown as diamonds. Letter symbols represent solar system planets. Placement of the Kepler exoplanets on mass-radius diagrams can be found in (25, 28). Circles represent transiting planets listed in the Extrasolar Planet Encyclopedia. The data to the right show planet density increasing with mass. The dashed line is the prediction for planets composed only of H and He and receiving irradiation associated with a Sun-like star at a distance of 0.045 AU (34). Rocky planets similar to Earth without atmospheres that contribute substantially to the mass of the planet are at the left. In between are ice giants, which are mixtures of H/He and rocky material (36).

Light curves and RV curves can be found in SOM text 5 and (25, 28–31). The results presented in the Tables 1 and 2 are based on time series of photometry and radial velocity data that can be retrieved from the Space Telescope Science Institute's Multimission Archive at STScI/ high-level science products (MAST/HLSP) data archive (32).

Kepler-4b is an exoplanet that is very similar in size, density, and mass to Neptune (the most probable estimates are 1.03 times the size, 1.09 times the density, and 1.43 times the mass) and is similar in mass and radius to GJ 436b (33). A major difference between Kepler-4b and Neptune is that the irradiance level for Kepler-4b is over 800,000 times larger than that of Neptune. However, the large difference in irradiance levels appears to make little difference to the sizes of the planets. The result implies a difference in bulk composition (34), with either a higher rock-to-water ratio or less H/He in Kepler-4b as compared with Neptune (and GJ 436b). The latter degeneracy cannot be resolved at this time.

The Kepler results did not find planets with very small values of semimajor axes (Fig. 1), even though such planets would have a larger probability of alignment than those with larger values. The stars associated with the Kepler exoplanets are generally larger than those shown in the Exoplanet Encyclopedia for transiting planets (Fig. 2). The difference could be due to the Malmquist bias or to the preferential selection of stars with sharp spectral lines for the Kepler follow-up; that is, slightly evolved stars.

The data add to the evidence for three planet populations (Fig. 3) and the separation between ice giants and gas giants. The scatter in the data might be explained by differing fractions of heavy elements and H/He envelopes (35, 36). However, it is surprising that Kepler exoplanets 5b, 6b, 7b, and 8b, as well as many other transiting planets shown in Fig. 3, also lie below the curve for a pure H/He planet (34). The radii of Uranus, Neptune, GJ 436b, HAT-P-11b, and Kepler-4b have been shown to lie below the predicted irradiated and nonirradiated radius-mass curves (25, 35).

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38. Kepler was competitively selected as the 10th Discovery mission. Funding for this mission is provided by NASA's Science Mission Directorate.

Supporting Online Material

www.sciencemag.org/cgi/content/full/science.1185402/DC1

SOM Text

Fig. S1

References

1 December 2009; accepted 28 December 2009

Published online 5 January 2010;

10.1126/science.1185402

Include this information when citing this paper.